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COMPARISON OF GEOSTATISTICAL METHODS FOR MODELING INFILTRATION TYPE URANIUM DEPOSITS

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Absrtract

Filtration process occurring during the formation of infiltration type deposits largely affects the geometry and content of uranium deposits, which creates a challenge when conventional methods of geostatistics are applied for geomodelling purposes. Verification of these methods is practically impossible since true picture of the deposit is never known. In this work authors use a synthetic model generated through reactive transport simulation accounting for specific characteristics inherent in deposits, which formed via infiltration process. Two conventional methods were tested: inverse distance weighting method and the method of kriging. Comparison shows, that in terms of resource estimation and if intrinsic parameters of the method are chosen correctly, inverse distance method can provide a higher accuracy as compared to kriging with various number of exploratory wells used.

Keywords: flow in porous media, reactive transport modelling, geostatistics, kriging, inverse distance weighting, infiltration type deposits.

Аннотация

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СРАВНЕНИЕ МЕТОДОВ ГЕОСТАТИСТИКИ ДЛЯ МОДЕЛИРОВАНИЯ МЕСТОРОЖДЕНИЙ УРАНА ИНФИЛЬТРАЦИОННОГО ТИПА

Процесс фильтрации, участвующий при формировании месторождений инфильтрационного типа, в значительной степени влияет на геометрию и содержание урановых месторождений, что создает проблему при применении традиционных методов геостатистики при геологическом моделировании. Верификация этих методов практически невозможна, так как нет сведений о истинной картине минерализации месторождений. В этой работе авторы используют синтетическую модель, созданную в результате моделирования реагирующего переноса с учетом специфических процессов, присущих образованным в результате процесса инфильтрации отложениям. В рамках проведенных работ были протестированы два традиционных метода: метода обратных взвешенных расстояний и метода кригинга. Сравнение показывает, что с точки зрения оценки запасов и при правильном выборе параметров, метод обратных взвешенных расстояний может обеспечить более высокую точность по сравнению с кригингом при различном количестве используемых разведочных скважин.

Ключевые слова: течение в пористых средах, реагирующий массоперенос, геостатистика, кригинг, метод обратных взвешенных расстояний, месторождения инфильтрационного типа.

Аңдатпа

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ИНФИЛЬТРАЦИЯЛЫҚ ТИПТІ УРАН КЕН ОРЫНДАРЫН МОДЕЛЬДЕУГЕ АРНАЛҒАН ГЕОСТАТИСТИКАЛЫҚ ӘДІСТЕРДІ САЛЫСТЫРУ

Инфильтрациялық типті кен орындарының қалыптасуына қатысатын фильтрация процессі уран кен орындарының геометриясы мен мөлшеріне аса әсер етеді, соның нәтижесінде геологиялық модельдеу барысында дәстүрлі әдістерді қолдану кезінде қиындықтар туады. Айтылған әдістерді верификациялау іс-жүзінде мүмкін емес, өйткені кен орнының нақты минерализация бейнесі туралы мәліметтер жоқ. Бұл жұмыста авторлар, инфильтрация процессі нәтижесінде қалыптасқан түзілімге тән, ерекше процесстерді ескере отырып, реакцияланатын тасымалды модельдеу нәтижесінде жасалған синтетикалық модельді қолданады. Жасалған жұмыстар аясында екі дәстүрлі әдіс тестіленді: кері өлшемді қашықтық және кригинг. Салыстыру нәтижесі, қолданылатын барлау ұңғымаларының әртүрлі сандары үшін, қорларды бағалау көзқарасынан және параметрлерді дұрыс таңдаған жағдайда кері өлшемді қашықтық әдісі кригингпен салыстырғанда жоғары дәлділікті қамтамасыз ететінін көрсетті.

Түйін сөздер: кеуекті ортадағы ағым, реакцияланатын массатасымалдау, геостатистика, кригинг, кері өлшемді қашықтық әдісі, инфильтрациялық типті кен орындар.

Introduction

Infiltration type deposits (ITD), which also have a high degree of reservoir oxidation, are also called “rollfronts”, and are an accumulation of minerals in porous medium (mostly sandstones) [1]. Deposits are formed due to the infiltration and precipitation of minerals; they are found in the redox fronts between oxidated and reduced environment.

Maksimova [2] considered the main factors in the formation of polyelement (uranium, molybdenum, selenium, rhenium, vanadium, scandium, ytrium, lanthanides) infiltration type deposits confined to aquifers of the sedimentary cover. Based on the generalization and analysis of hydrodynamic data, the ore-controlling bedded epigenetic zonality and the behavior of various chemical elements in the ore-forming process, the paper determined that the hydrodynamic factor is the main factor in the formation of ITD. Thus, ITD deposits can appear only in artesian basins with an infiltration hydrodynamic regime.

Dahlkamp's works [3, 4] present a broad overview of the features of the geological structure of uranium deposits, and a generalization of these data in the form of a typological classification with a detailed description of individual uranium regions and deposits. The paper presents various types of deposits and the specifics of their formation, including epigenetics. In [4], the distinctive characteristics of ITD are given, described as deposits, which are bandy sections of inclusions of the minerals, limited by weakly permeable beddings from top and bottom. Mineralized zones consist of elongated and curved fronts directed along permeable layers and perpendicular to the flow of groundwater. Mineralized zones have a convex shape down the hydrological gradient. They have indistinct borders with reductant filled environment downstream of the water flow and contrast boundaries with oxidized media in upstream (Figure 1).

In particular case, ore formation began with the rising of the Tien-Shan mountain range, which supplied with minerals an adjacent Megatien-Shan province (Southern Kazakhstan) basin from the south and provided uranium and other ore-related elements.

In the work of Yazikov [5], a list of hydrogeological factors affecting the profitability of production of ITD is determined, in particular: lithological composition and thickness of water-bearing rocks; depths of occurrence of aquifers and groundwater levels, the nature of groundwater development; direction of movement and speed of the natural flow of groundwater; underlying and blocking aquicludes; filtration properties of rocks of the ore-bearing horizon.

The paper [6] highlights the regularities and duration of the formation and placement of uranium deposits. The following subtypes of deposits are distinguished: roll (fronts of reservoir oxidation, also known as ITD), reservoir, near-fault-stratal and paleovalley.

Of great importance in the formation of uranium mineralization are various hydrodynamic regimes of groundwater [7]. The distribution of groundwater is determined by the surface topography, and is determined by the forces of gravity. During their ore formation, the permeability of ore-bearing rocks and the presence of a geochemical barrier in the zone of wedging out of chemically oxidized rocks are of decisive importance. The water regime, together with the composition of rocks, determines the morphology of ore bodies, the texture and structure of ores.

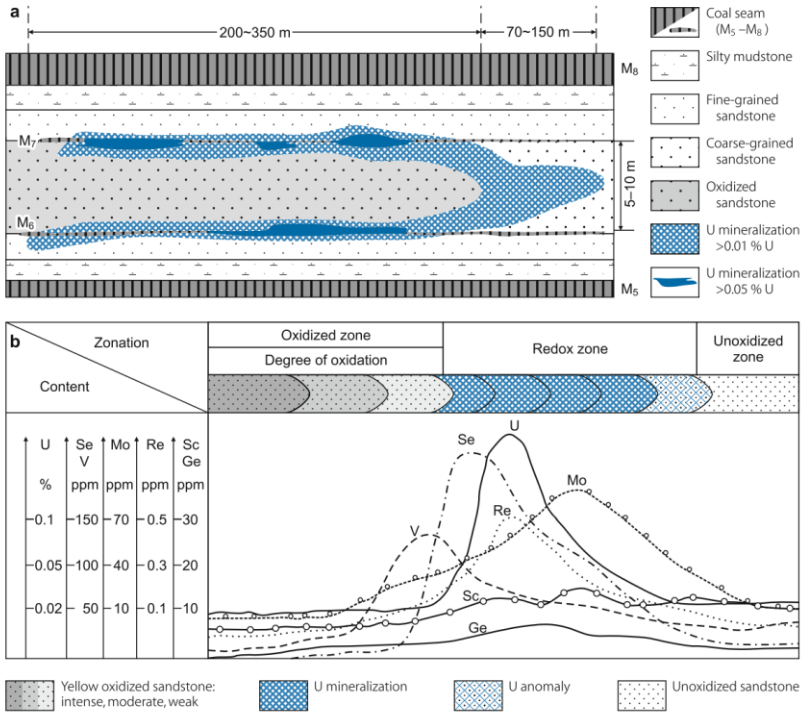

Figure 1. The form of mineralization in the form of "rolls" in the ITD. The concentration of various components along the flow of groundwater relative to the oxidized and reduced zones is shown [3,4]

In the work of Tarkhanov [8], the regularities of the spatial distribution of uranium and the factors contributing to the formation of large deposits are considered. A formula for estimating potential resources is proposed that takes into account the following factors: initial and residual uranium content in solutions, rock permeability, hydraulic head, duration of ore formation, and the degree of contrast of the redox barrier.

As a result of the review of works on the study of hydrodynamic and hydrogeological processes of the formation of ITD, the following factors were identified, taken into account by the authors when building a hydrodynamic model:

1) gravity is the cause of the movement of groundwater, therefore the flow in the reservoir is due to the presence of a hydraulic slope;

2) filtration characteristics affect the final geometry of the ore body;

3) ITD usually have upper and lower impermeable layers;

4) the final form of mineralization in top view looks like a winding ribbon and a crescent-like (elongated tongue) in a vertical section.

Verifying the accuracy of geostatistical methods is one of the major challenges in geological modeling, as the actual mineralization pattern is never known. Existing technologies do not allow a full reservoir scan to determine in detail the actual distribution of mineral concentrations (or other characteristics) to determine the accuracy of the results of geostatistical methods.

The aim of current work is to provide an instrument for generating synthetic infiltration type deposits to verify and compare existing stochastic methods. A synthetic deposit is a computational grid (3D data array) with known, real values of mineral concentration in each of its nodes. By placing exploratory wells with different configurations, well data can be collected, on the basis of which geostatistical calculations could be carried out using traditional methods. To analyze the accuracy of the methods, the results obtained are then compared with known values.

Simulation of synthetic infiltration type uranium deposit

The mathematical model of water filtration in a permeable porous reservoir is described by the Darcy and mass conservation laws [9]

$$\nabla \cdot \vec{u} = 0 \quad (1)$$

$$\vec{u} = -k_f \nabla \mathrm{H} \quad (2)$$

where $\vec{u}$ – solution filtration velocity, k_f – stratum filtration coefficient, $H -$ stratum hydrodynamic head.

Substituting equation (2) into equation (1), we obtain an elliptic type equation, which is solved by the over-relaxation method

$$\nabla \cdot (k_f \nabla H) = 0 \tag{3}$$

In [10], in a 2D formulation, using Comsol Multiphysics, a preliminary study of influence of the hosting domain shape, filtration properties and chemical reactions on the geometry and content of the deposit was carried out. In the framework of this work, a preliminary 3D software functionality has been developed for studying the processes of formation of ITD. The developed software functionality was used to generate a test geological model of the ITD field. The authors considered an area in the form of a parallelepiped with a computational domain shown in Figure 2. The Neumann boundary condition was set on the upper and lower walls, which corresponds to the presence of impenetrable layers:

$$\left.\frac{\partial p}{\partial n}\right|_{sides} = 0 \tag{4}$$

The hydraulic slope is described by the following boundary conditions at the inlet and outlet of the domain:

$$\begin{gathered} p|_{in} = p_{atm} + \rho g h \\ p|_{out} = p_{atm} \end{gathered} \tag{5}$$

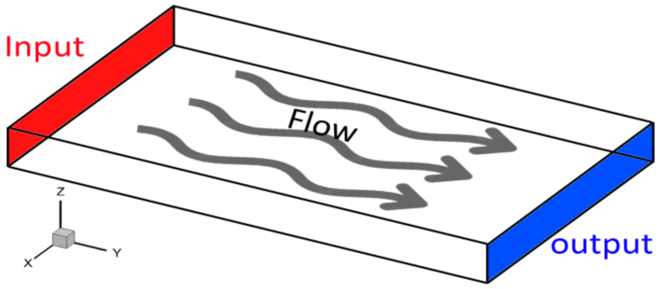

Figure 2.Calculation domain

Heterogeneous distributions of the filtration coefficient in the reservoir were considered. The non-uniform distribution was obtained by the following formula (Figure 3):

$$Kf_{i,j,k} = (2 + sin\frac{\pi k}{(N_z - 1)}(\sin \pi i + \cos \pi j))R \tag{6}$$

where $Kf_{i,j,k}$ – the value of the filtration coefficient in the grid node i, j, k, N_z – number of grid nodes along the *Z*, and *R* axes range of allowable K_f values.

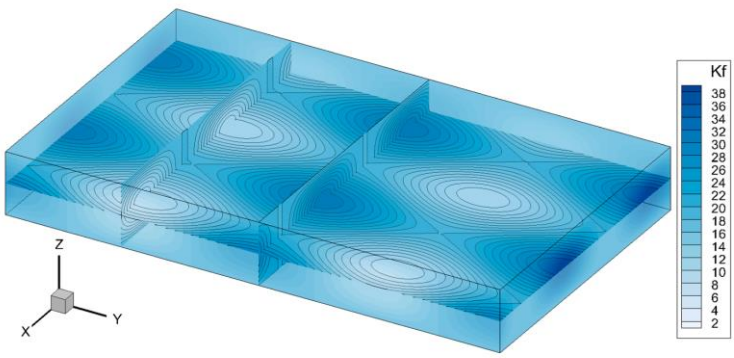

Figure 3. Heterogeneous distribution of permeability in the reservoir

Based on the pressure field found from the Darcy law (2), the velocity field is determined, which is subsequently used to study the transport of dissolved mineral and its deposition in the reservoir. The resulting pressure distributions and streamlines are shown in Figure 4.

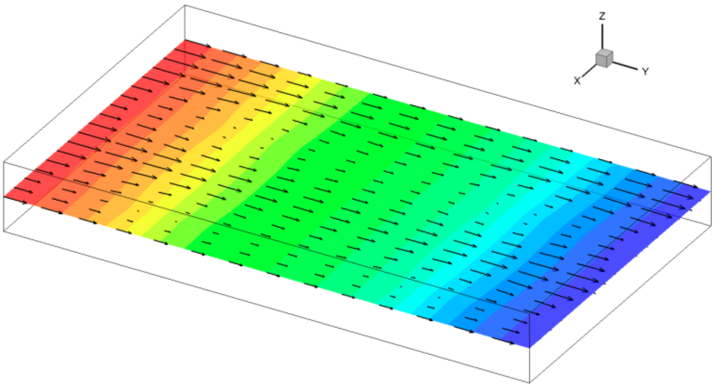

Figure 4. Distribution of pressure and velocity in the reservoir

The velocity field was used to simulate the mass transport of the mineral during the filtration of the solution in the reservoir, and to obtain a synthetic uranium ITD.

Comparison of the effectiveness of geostatistical methods as applied on generated synthetic infiltration type uranium deposit

Domain was covered by a set of virtual exploration wells from which ore intervals are collected, that are accepted as input data for geostatistical methods. The aim of the methods is to restore the mineralization pattern as close as possible to the fact based on well data. Geostatistical estimation methods are based on assigning a weight of influence value λ_i for nodes where data is known each located at x_i position to determine the value of mineral concentration $Z^*(x)$ at an arbitrary point x:

$$Z^*(x) = \sum \lambda_i Z(x_i)$$

Fundamentally, the methods differ in the algorithm for determining the weight. Two methods of geostatistics that are often used to reconstruct the reservoir geological model were considered: the inverse distance weighted (IDW) method and the kriging method. Using the constructed test geological model, the methods of inverse distances weighting and the kriging method were evaluated. In the IDW method, the calculation of values at any point are determined according to the following formula [11].

$$Z^*(x) = \sum_{i=1}^{n} \frac{\frac{1}{d_i^p}}{\sum_{i=1}^{n} \frac{1}{d_i^p}} Z(x_i) \tag{7}$$

where d_i is the distance between point x and x_i, calculated by the formula $d = \sqrt{a(x-x_i)^2 + b(y-y_i)^2 + c(z-z_i)^2}$, a, b, c are the coefficients characterizing the anisotropy of the formation.

In the kriging method, the value of influence weight is calculated from the selected semivariogram model to determine the statistical nature of the reservoir. The construction of a variogram is carried out according to the following formula [11]

$$\gamma(h) = \frac{\overline{(Z(x+h) - Z(x))}^2}{2} \tag{8}$$

where the value of the semivariogram function $\gamma(h)$ is equal to half the square of the means of all points that are approximately at distance h from each other. By selecting several arbitrary distances h and the discontinuous semivariogram curve is calculated under which the model is selected.

Using the notion of a covariogram in the form:

$$C(h) = C(0) - \gamma(h),\ C(0) = \sigma_x \tag{9}$$

the weight λ_i of each known point x_i is calculated by solving the following matrix equation:

$$\begin{bmatrix} C(x_1-x_1) & C(x_1-x_2) & \dots & C(x_1-x_n) & 1 \\ C(x_2-x_1) & C(x_2-x_2) & \dots & C(x_2-x_n) & 1 \\ \dots & \dots & \dots & \dots & \dots \\ C(x_n-x_1) & C(x_n-x_2) & \dots & C(x_n-x_n) & 1 \\ 1 & 1 & \dots & 1 & 0 \end{bmatrix} \begin{bmatrix} \lambda_1 \\ \lambda_2 \\ \dots \\ \lambda_n \\ \mu \end{bmatrix} = \begin{bmatrix} C(x-x_1) \\ C(x-x_2) \\ \dots \\ C(x-x_n) \\ 1 \end{bmatrix} \quad (10)$$

A test synthetic geological model obtained as part of the work was used to compare the methods of inverse distance weighting and kriging.

Implemented functionality was used to cover the test block with a network of exploration wells, the number of which varied. Along each well, with a given frequency, data is collected, which are then used as input parameters for geostatistical methods (Figure 5).

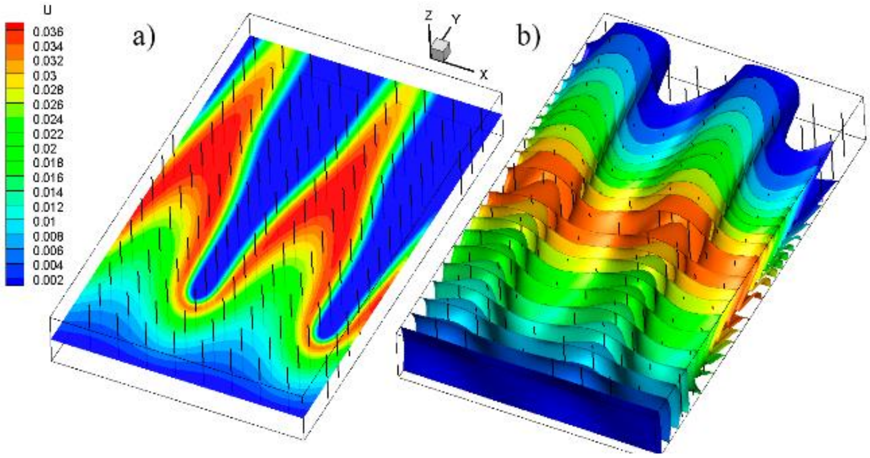

Figure 5. Distribution of the mineral in plan (a) and is osurfaces of the mineral content (b) in the reservoir

Developed software was used to perform the interpolation using the kriging and IDW methods. Figure 6 shows the resulting initial test geological model and the qualitative results of interpolation by the methods of IDW and kriging.

a) b) c)

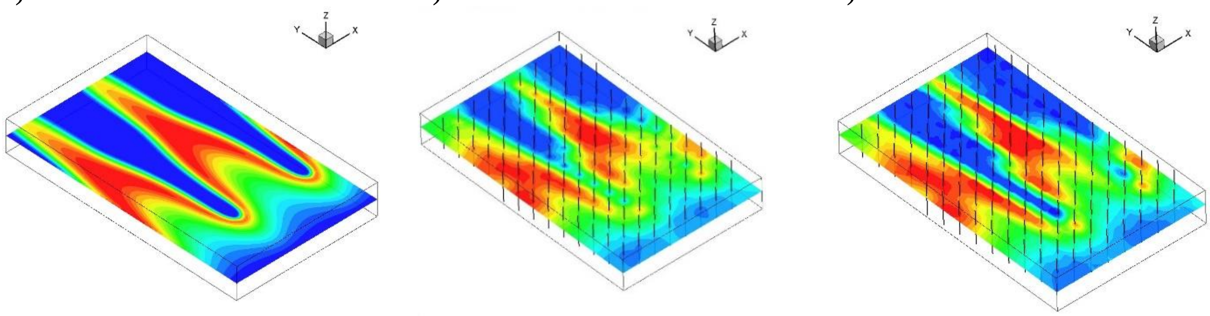

Figure 6. Initial mineral distribution in the reservoir (a), field models reconstructed by inverse distance (b) and kriging (c)

Qualitatively, kriging shows a better picture in comparison with IDW, with a lower average and maximum error for all grid nodes.

For quantitative analysis, the mineral reserves were compared, according to the results of geostatistical methods, with the true value for a different number of exploration wells used. The mineral reserves are calculated by the following formula

$$Reserves = \sum_i \frac{c_i}{100} \rho V_i \quad (11)$$

where c is the concentration of the mineral, ρ is the density of the ore body, V_i is the volume of the i^{th} node of the computational grid.

The results show (Figure 7) that the accuracy of both methods is highly dependent on the number of exploration wells. To improve the accuracy of calculating reserves in the reservoir, it is recommended to increase the number of exploration wells. Applied to ITD fields, IDW provided a more accurate estimate of reserves with different numbers of wells.

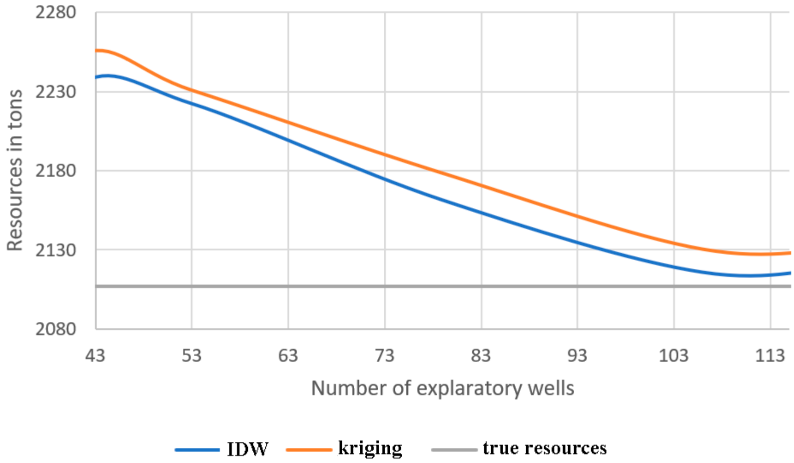

Figure 7. In-situ uranium reserves calculated using test and reconstructed geological models by different methods

Conclusion

Infiltration type deposits have untypical geometry as well as distribution of mineral concentration attributed to the process of their formation as compared to sedimentary deposits. Sedimentary hosting environment generally has a horizontal anisotropy, while choosing correct anisotropy parameter becomes a challenging process due to heterogeneity of such deposits. However, reactive transport simulation can be used to mimic the infiltration and chemical mass transfer processes participating in the formation of these mineralizations to generate a testing model with all inherent parameters which can be attributed to infiltration type deposits.

A synthetic deposit has been generated in this work for verification purposes. Exploration process has been simulated with varying number of boreholes to obtain log data as input information for geostatistical methods. Two methods have been implemented and used to model the deposit based on well log data. To obtain quantitative data resource estimation process has been conducted on verification model, and on the results of both kriging and IDW. While kriging accounts for inherent variability with variogram models, it is generally harder to choose appropriate variogram model. IDW, however, is a much simpler and less resource intensive method. Comparison shows that in all cases (with varying number of wells) inverse distance method is slightly more accurate than kriging.

Current work demonstrates, that geostatistical methods can be verified with appropriate application of reactive transport simulation techniques. This technique can not only be used to compare the performance of other stochastic methods, but also to develop and verify a future method specific to infiltration type deposits.

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